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An overview of ocean renewable energy in China

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ABSTRACT

Facing great pressure of economic growth and energy crisis, China pays much attention to the renewable energy. An overview of policy and legislation of renewable energy as well as status of development of renewable energy in China was given in this article. By analysis, the authors believe that ocean energy is a necessary addition to existent renewable energy to meet the energy demand of the areas and islands where traditional forms of energy are not applicable and it is of great importance in adjusting energy structure of China. In the article, resources distribution and technology status of tidal energy, wave energy, marine current energy, ocean thermal energy and salinity gradient energy in China was reviewed, and assessment and advices were given for each category. Some suggestions for future development of ocean energy were also given.

Contents

1. Introduction

China's economy has been rapidly growing for more than 30 years. Since entering the new millennium, the average growth rate of China's GDP exceeds 10% [1]. Preliminary accounting, annual gross domestic product (GDP) of 33.5353 trillion CNY in 2009, annual GDP growth of 8.7% over the previous year [2]. Correspondingly, the energy requirements and consumptions in China have kept an annual growth since the year 2000. After 2001, economic growth continued apace, but energy demand growth surged to 13% a year. In 2001 China accounted for 10% of global energy demand but met 96% of those needs with domestic energy supplies; today China's share of

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global energy use has swelled to over 15%. China is now the world's second-largest energy consumer [3]. According to preliminary estimation of 2009, the total energy consumption of China reached 3.10 billion tonnes of coal equivalent, with an increase of 6.3% from 2008 and 124% from 2000. And the total electricity consumption reached 3.697 trillion kWh, with an increase of 6.2% from 2008 [2]. According to estimation, before 2020, China's annual GDP will be continue to increasing at an average rate of 8% [5]. Predicably, China's energy requirement will be rising in near future with its economy development [4].

Coal has been predominated the primary energy consumption composition of China, [21] accounts for 68.7% and 76.2% in 2000 and 1990 respectively, and kept more than 68.7% in recent years, compared to the world average of 24% [10]. The coal consumption of 2008 reached 2.74 billion tons, making up 68.7% of total output and 3.02 billion in 2009, up to 9.2% [6,9]. And, China uses more coal than the total consumption of USA, EU and Japan [11]. Other fossil fuels consumption also increased. Crude oil consumption reached 0.38 billion tons and gas consumption 88.7 billion cubic meters, grow by 7.1% and 9.1% compared to the previous year respectively [2,6]. However, China is short of energy resources, of which reserves of fossil fuels are lower than the world's average. Proved coal reserves so far can only meet the needs for 80 years. Crude oil has been import dependency for a long period, with importing proportion more than 40% since 2004 and nearly 50% at one time [7,8,20]. It was estimated that in China the oil resources will be exhausted by 2040, natural gas by 2060 and coal by 2300 [12]. And even worse, China's energy efficiency is comparatively low. China's energy intensity (0.91 tonnes oil equivalent per thousand US$ GDP at 2000 prices in 2005) was much higher than the world as a whole (0.32) [20]. Low energy efficiency further intensified China's energy consumption, made the situation even worse.

Massively use of fossil fuels also brought about serious environmental problems. Burning coal is the principal agent responsible for air pollution, water shortages, polluted soil, ecosystem degradation, and widespread human illness [13]. The main problems caused by massive consumption of fossil fuels, especially coal, are emission of greenhouse gases (GHGs) and global warming. In 2005, coal accounted for 42% of global CO_2 emissions. In that year, coal combustion accounted for 82% of China's CO_2 emissions [14,15]. As the world's second-largest energy consumer, China is by far the biggest contributor to incremental emissions, overtaking the United States as the world's biggest emitter in 2006 [3,16,20], Premier Wen Jiabao promised on behalf of Chinese government that China would cut CO_2 emissions intensity by 40–45% below 2005 levels by 2020 on the 2009 United Nations Climate Change Conference [17]. This promise fully embodies the positive attitude of Chinese government to the world and determination to change economic growth mode from high energy consumption and pollution to sustainable development.

High speed growth of economy, increasing demand for energy and requirement for reduction of GHGs emission has laid great pressure on China. In light of China's current energy conditions, to promote energy efficiency and to adjust energy structure, and to raise the proportion of renewable energy in overall energy mix are the only way to maintain sustaining economic development while keeping constant or even decreasing the pressure on environment and to achieve the goal of reduce GHGs emission by 40–45% from 2005 [18,19]. Although China has made great efforts in this aspect and great progress has been made on wind and solar power, the renewable energy's proportion in the whole energy mix is far below the world average [20]. On the basis of current situation, it is necessary for China to development various types of renewable energy to meet the growing demand for economy development while releasing the environmental pressure caused by usage of fossil fuels.

China boasts a mainland coastline of more than 18,000 km and a sea area of more than 3,400,000 km^2 with abundant ocean energy resources. Developing ocean energy bears enormous strategic significance for China's sustainable development [6]. As one class of renewable energy, although ocean energy currently shares a very small proportion in energy system, it has great potential for development. This article makes investigations and analysis about China's renewable energy, especially the research on ocean energy's utilization and situation in order to forecast and give advice on development of ocean energy in the future, help researchers learn current research status and explore research orientations and help decision making and investment for relevant groups.

The second part of this article will discuss significance and availability of exploiting China's ocean energy on the basis of an overview of the development of China's renewable energy and the strategic plan made by Chinese government. The third part will give an overview of China's ocean energy and research status of it in categories. The article will be ended with some conclusions and suggestions about the development of China's ocean energy.

2. Current situation of renewable energy in China

Chinese government has been committed to developing renewable energy for that it is of strategic significance to keep balance between energy demand and supply.

2.1. Energy structure and development strategy of China

2.1.1. Sectors of renewable energy and situation of energy structure in China

In *the Middle and Long-Term Program of Renewable Energy Development*, the key areas of renewable energy's development from 2010 to 2020 are defined as hydro energy, bio-energy, wind energy, solar energy and other renewable energy (including geothermal energy and ocean energy) [22].

With the increase of the total energy production, the proportion of renewable energy in China's total energy mix is also on the rise. The proportion of renewable energy (including hydroelectric power, wind energy and nuclear power) in annual total energy consumption was 7.2% in 2006, compared with 7.3% in 2007 (as shown in Fig. 1) and 8.89% in 2008 [1,9]. According to this trend, although challenging, it is possible for China to achieve the goal set in *the*

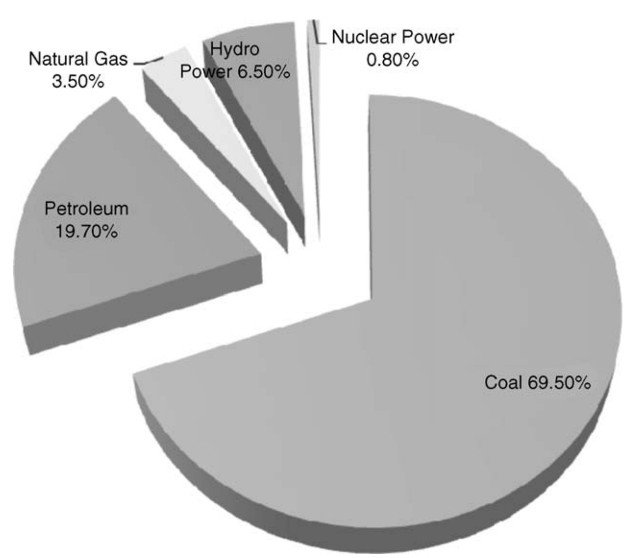


Fig. 1. Primary energy composition as percentage of primary energy production (%) (Coal equivalent calculation) in 2007 [9].

Middle and Long-Term Program of Renewable Energy Development that the proportion of China's renewable energy consumption in total energy consumption mix reaches 10% by 2010.

2.1.2. Strategic planning of renewable energy's development in China

2.1.2.1. Policy and legislation. As a signatory of the *United Nations Framework Convention on Climate Change*, China's renewable energy development strategy keeps pace with the world's sustainable development. After the *United Nations Conference on Environment and Development* (UNCED) in 1992, China worked out *China's Agenda 21* in 1994 in which the overall strategic planning of sustainable development of China was established. It is pointed out in Chapter 13 of the document that renewable energy, including hydroenergy, solar energy, wind energy, biomass energy, geothermal energy and ocean energy, is the basis of future energy structure and China must take the road of sustainable energy development [23,24].

In 1995, the State Planning Commission (SPC), State Science and Technology Commission (SSTC) and State Economic and Trade Commission (SETC) jointly worked out *The development outline of China's new energy and renewable energy from 1996 to 2010* and re-emphasized the importance of the development of new energy and renewable energy to China's economic sustainable development and environmental conservation, while the prior development programs were also marked out [25]. *The electricity law of the people's republic of China* went into effect in 1997, and *China's Energy Conservation Law* (ECL) was approved on 1 November 1997 and came into force on 1 January 1998 [26–29]. Both laws clearly pointed out that the state encourages the development and utilization of new energy and renewable energy, which brought this sustainable industry under a system of laws. In order to carry out ECL in 2001, SETC worked out *The development outline of China's new energy and renewable energy from 2000 to 2015* in which set the medium-term goal of developing new energy and renewable energy. It said that by the year 2015, China's utilization capacity of new energy and renewable energy should reach 43 million tonnes of coal equivalent, sharing 2% of the national total energy consumption mix (excluding the utilization of traditional biomass energy and small scale hydroelectric power) and 80 million tonnes of coal equivalent, sharing 3.6% of the total, if small scale hydroelectric was included.

The Renewable Energy Law of the Peoples' Republic of China issued in Feb. 28, 2005, which was considered to be a milestone of China's development of renewable energy [30]. The Renewable Energy Law is the first attempt to implement a national framework for the development of all sectors of the industry and to create targets for the share of the total electricity market held by renewable energy. The Law provided the framework for some important legislative initiatives, designed to secure the strategic position and future development of renewable energy and went into effect on Jan. 1, 2006, followed by a number of supporting laws and regulations [31,32]. From 2006 to 2008, 12 detailed regulations for promoting renewable energy development were formulated [33].

On 26 December 2009, the 12th Meeting of the Standing Committee of the 11th National People's Congress adopted the decision of the Standing Committee of the National People's Congress on amending the Renewable Energy Law of the People's Republic of China in which the Renewable Energy Law was amended and would put into effects on April l, 2010 [34]. In fact, the actual amendments to the law are extremely minor.

It shows that Chinese government attaches great importance to energy issues. A series of measures has been carried out including gradually completing the legislation of renewable energy, enacting laws and regulations, formulating the development framework, establishing the principles of developing renewable energy and ensuring the implement of the policy of renewable energy. And all these measurements are constantly under improvement.

Chinese government has formulated a serious of priority economic policies to promote the development of renewable energy, mainly including tariff reduction and exemption, value-added tax policy, tax shelter, soft loan, economic incitement and subsidy, etc.

Policies of Chinese government on the research and development of renewable energy are embodied in two aspects, on one hand giving massive subsidies and financially aiding the research and development of renewable energy, on the other supporting the development of renewable energy and starting up several major development programs [35]. Since the period of China's 6th year plan, in order to support the scientific research and new technology of new energy and renewable energy, development of new equipment, and construction of demonstration project and industry development, SPC, SETC and SSTC have been providing financial aiding through some special funds, which played an important role in improving the level of new energy and renewable energy's technical equipment, the development and utilization scale and industry development with product quality and serve system. During the time from 1980 to 1999, the total research and development funds invested by National Programs for Science and Technology Development are nearly 200 million CNY and the loans invested by State Torch Plan, Spark Program and Technical Innovation Program reached 2 billion CNY which effectively promoted the development and utilization of renewable energy [36]. After two decades of hard work, China has made huge progress in development of renewable energy. Technical level had been greatly raised, the market had expanded continuously and the industry of renewable had begun to take shape. In China's *10th Five-Year Plan for National Economic and Social Development* which set up in 2001 re-emphasized to develop new energy such as wind energy, solar energy, geothermal energy, etc. and further increased governmental investment to renewable energy. "Introducing preferential fiscal and taxation policies, investment policies and mandatory market share policy, encouragement in producing and consuming renewable energy and improving the proportion in the primary energy consumption" is pointed out in the *outline of the eleventh five-year plan* in 2006, brought up the specific goal about wind energy and biomass energy with the proposal to develop and utilize solar energy, geothermal energy and ocean energy [37]. By the end of 2006, China's annual investment in renewable energy reached 5 billion dollars, ranking second globally behind Germany [38].

2.1.2.2. China's strategic plan for developing renewable energy. - China has brought the development of renewable energy into the whole planning system of national economy and made systematic and detailed strategic plan for development of renewable energy. *The Outline of the 11th Five-Year Plan for National Economic and Social Development of the People's Republic of China* projects that the per-unit GDP energy consumption by 2010 will have decreased by 20% compared to 2005, and the total amount of major pollutants discharged will have been reduced by 10% [35].

In 2005, the Chinese government promulgated the *Outline of the National Plan for Medium- and Long-term Scientific and Technological Development* (2006–2010), which gives top priority to the development of energy technologies, and, in line with the principle of making independent innovations and leapfrogging development in key fields, shoring up the economy and keeping in step with leading trends, stresses accelerating progress of energy technologies and strives to provide technological support for the sustainable energy development [39].

The*11th Five-Year Plan for Development of Energy*, which published by the National Development & Reform Commission

(NDRC) in 2007, pointed out that during the fifth Five-Year period, China will prioritize renewable energy resources with high potential and proven techniques such as wind energy, biomass energy, BBDF, solar energy, etc. and promote the industrialization by scale construction [40].

In the same year, NDRC published the *Medium and Long-Term Development Plan for Renewable Energy in China*. It put forward the guiding principles, objectives and targets, priority sectors, and policies and measures for the development of renewable energy in China up to 2020 [41]. It set the goal of increasing renewable energy consumption to 10% of the total energy consumption by 2010 and 15% by 2020 [35]. The following *The Fifth Five-Year Program for Development of Renewable Energy* laid out the development of renewable and set detailed goals for each sector [37].

The State Council Information Office of the People's Republic of China published *China's Energy Conditions and Policies* [35]. The white book gave a detailed introduction on China's present situation of energy development, strategies and goals of energy development and measures on promoting energy conservation on a full scale, enhancing the capability for the supply of energy, achieving balanced development between the energy industry and environment, intensifying the reform of energy system, strengthening international cooperation in energy area, etc.

It can be seen that China has formulated a series of policies to solve energy issues and develop renewable energy. In order to guarantee the execution of these policies and increase efficiency, China has spared continuous efforts in administrative reform. A Ministry of Energy was established in 1988 but it was disbanded 5 years later because its administrative functions overlapped with other departments. The government set up an Energy Bureau under the NDRC during administrative reforms in 2003. The National Energy Administration (NEA) was set up in 2008 but it lacks the power to carry out many of its assigned tasks as responsibility for the energy sector is currently spread among a number of departments. Then China's State Council decided to set up National Energy Commission (NEC) in Jan 2010, with Premier Wen Jiabao as head and Vice-Premier Li Keqiang as the deputy. The commission will be responsible for drafting national energy development plans, reviewing energy security and coordinating international cooperation. It has 21 members, including ministers from various organizations such as the National Development and Reform Commission (NDRC), and the Ministry of Finance, as well as a representative from the central bank [42].

2.2. The development situation and prospect of renewable energy in China

China's renewable energy industry is growing rapidly. At the moment, renewable energy (excluding traditional biomass) accounts for more than 8% of China's energy and 17% of electricity supplies. However, even though this figure represents a notable increase in the use of renewable, it is dwarfed by China's use of coal, which supplies almost 70% of the country's energy needs [33].

In recent years, wind energy and hydroelectric power grows fast in China's energy production and supply, so does the nuclear power. China is now the largest hydropower generator in the world, accounting for 14% of the world's total hydro production. The Three Gorges Dam is now the largest hydropower station in the world with an 18.2 GW rating. Hydro electricity is by far China's largest supplier of renewable energy [43]. In 2007, China had an installed capacity of 118 GW and generated 423 billion kWh. Hydro electricity accounted for about 15% of the country's total, increasing by 117% of 2008 and about four times of 1990. Nuclear power capacity reached 684 kWh in 2008, which is four times of the number in 2000 [6]. Wind energy is the fastest-growing renewable energy in recent years and wind is the second leading source for renewable power in China [44,45]. China's installed wind power capacity reached 12 million kW by the end of 2008, which was a 25-fold increase since 2000, and ranking the fourth globally trailing the United States, France and Spain. China is also the world's fastest-growing installer of wind, it is expected to reach above 5000 MW by 2020. The solar photovoltaic in China was also developed largely, but with a relatively low installed capacity, which was about 140 MW by 2008 [6]. China is the world's largest producer and exporter of solar cells (PVs) [46]. In 2008, China manufactured nearly 40% of all PV cells in the world [47,38]. Biomass so far plays a relatively small role overall, but is important in some niches. China is already the world's third largest producer of fuel ethanol (2.9% of world's total in 2008) [11]. In rural areas, the goal is 80 million households, or roughly 300 million people, taking biogas as their primary source of energy [41].

According to the targets set by the government in the *Medium and Long-Term Development Plan for Renewable Energy in China*, share of renewable energy of total primary consumption will be 10% by 2010 and 15% by 2020 [40,37]. The two main sources of renewable energy for China will be from hydropower and wind power. Hydropower is expected to reach a capacity of 190 GW by 2010 and 300 GW by 2020. Wind energy, is expected to reach 10 GW by 2010 and 30 GW by 2020. Biomass is expected to reach a capacity of 5.5 GW by 2010 and 30 GW by 2020. Solar is expected to reach 300 MW by 2010 and 1.8 GW by 2020 [37,48,43].

2010 is the last year of the China's 11th Five-Year Plan. The current situation shows that the renewable energy development target set in the 11th Five-Year Plan would be surpassed. It is possible that the long-term goal set in the *Medium and Long-Term Development Plan for Renewable Energy* could also be reached, even overfulfiled. In the 3rd China Environmental Investment Conference, which held from 25 to 26, Apr. 2010, some experts revealed that the national departments of energy were discussing on amending renewable energy's development planning in which the proportion of the renewable energy in the total energy consumption by 2020 is expected to be raised to 17% from 15% [49].

2.3. Assessment of renewable energy development in China

Although renewable energy has been greatly developed in China than before, there are still some issues need to be solved. Above all, the proportion of renewable energy is still very low and there is a long way to go to reach the target [50].

Another point should be noticed is that a large proportion of China's renewable energy comes from hydroelectricity and nuclear power while the impacts on environment caused by these two kinds of energy needs revaluation. The development of hydroelectricity has been a controversial issue in the world and there are also different voices in China. Many experts take dim view of impacts caused by dam construction on environment and eco-system. And there were lessons of Sanmenxia Project in the history of China. In 2006, China halted work on building 22 major dams and power stations because the Chinese State Environment Protection Agency stipulated that the projects, worth a total of US$14.65 billion, could not proceed until their environmental effects had been considered. [31]. The nuclear power has been widely criticized for its safety and disposal of nuclear wastes. Therefore, neither hydropower nor nuclear power, are regarded as truly renewable sources. Chinese Government is more and more cautious of the development of these two kinds of energy. By now China's renewable energy only accounts for less than 3% of the country's total power generation excluding power from large hydro projects and traditional biomass.

According to the two points mentioned above, it is far from being satisfied with the situation of renewable energy in China. It's

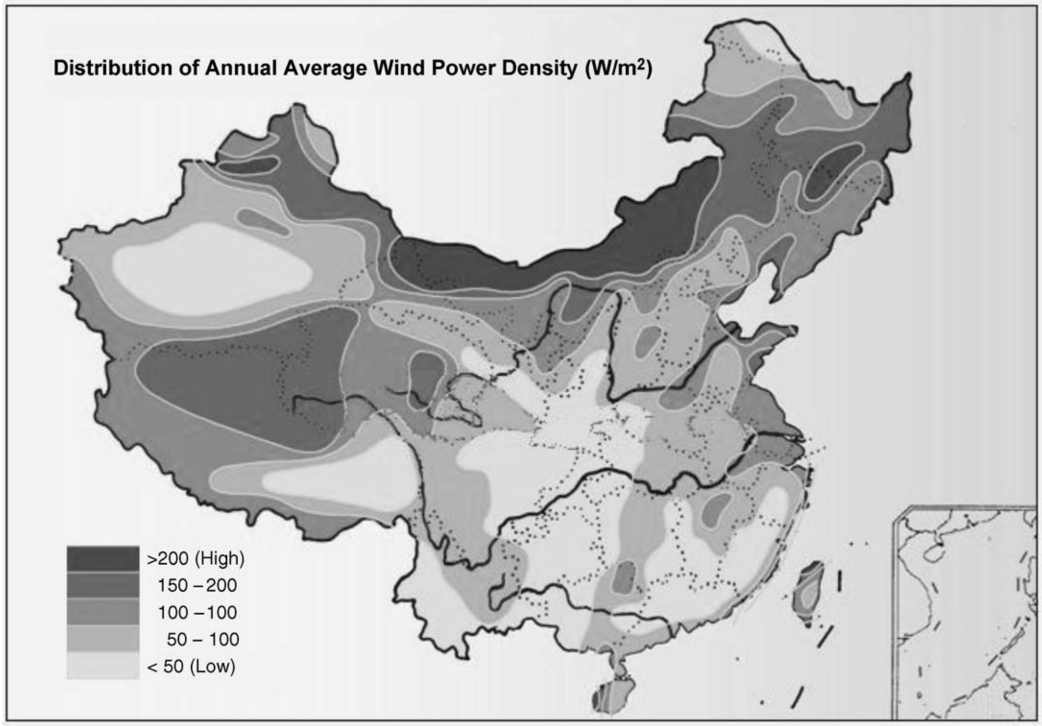


Fig. 2. Distribution of wind energy resources in China (Courtesy of Center for Wind and Solar Energy Resources Assessment of China Meteorological Administration).

necessary for the government to strive to develop other kinds of renewable energy than nuclear power and hydroelectricity. As it is, after being developed in the period of the 11th Five-Year, the techniques of biomass energy, wind energy, solar heating energy and solar photovoltaics energy generating in China are relatively mature, and have formed certain scale. Especially the wind energy and solar energy are accounting for an increasing percentage in the energy structure of China.

It is noticed that the reserves of wind energy and solar energy are geographically unbalanced. Although a research shows that wind could theoretically accommodate all of the demand for electricity projected for 2030, about twice of current consumption [51], as shown in Fig. 2, the wind energy sources of China are mainly located in the northwest provinces, the plains and deserts of Inner Mongolia, the southwest and northeast mountain areas and a few coastal regions [52,53,45]. The Northeast, North China and Northwest are the richest wind energy areas with flat terrains for the wind farms, convenient transportation and no destructive wind velocity. It is the largest tract of land with wind energy sources which is suitable for building large scale wind farms. But relatively small capacity of local electric grid hampered the scale of wind power and long-distance transmission is needed for long way to the load center. Within the limits of 10 km along the southeast coastal including the islands are also rich resources region of wind energy where the wind farms are convenient to connect to grid and seasonally complementarity to the hydro-electricity. But unfortunately, it is difficult to utilize the resource because of the restricted area to install the wind turbines as the aquacultural grounds and forest shelter belts have been built in these coastal areas. China's solar energy resources are shown as Fig. 3. The regions that have the richest solar energy resource are Tibet, Qinghai, Xinjiang, the South of Ningxia, Gansu and Inner Mongolia, while the southeast part of China is poor in solar energy [54,46]. However, the power consumption in the southeast coast of China is much higher than the other areas for its developed economy and large population density [55,56]. In order to solve the issue of unbalance distribution of economy and energy resources between eastern and western parts, China has started up the West–East Power Transmission Project. Total investment to the project has reached more than 52.65 billion CNY since 2001. Although the investment was enormous, the issue could not be completely solved yet. In terms of the distribution of energy resources, although wind energy and solar energy could raise the proportion of renewable energy in China's overall energy production, they could do little to help solve the power shortage of Southeast China.

Energy industries, such as wind power, biomass energy and solar energy in China have been advancing faster than expected. Many problems arise, in particular, early presentations of hasty profit-oriented projects, inappropriately planned work that rushes into implementation, and out of order while ignoring the availability of resources [31]. According to the data provided by a department of National Energy Administration (NEA), the installed capacity of wind power in China has reached 22 million kW in 2009, far exceeded the target of 2010 [49]. Therefore, it is thought that there is evidence of surplus in wind energy and solar energy [32,57,58,54].

In conclusion, in order to continuously increase the proportion of renewable energy in the whole energy mix and achieve the targeted goal, China must strengthen the efforts to develop and utilize other kinds of renewable energy as well as wind energy and solar energy. Liu Qi, deputy director of NEA, revealed in the National Committee of the Chinese People's Political Consultative Conference (CPPCC) on 8th Mar, 2010, that the NEA is working on the new energy development plan, adjusting the medium and long-term development planning of nuclear energy, making great endeavors to adjust the energy structure and speeding up the development of renewable energy and nuclear energy, especially the rising sectors of energy such as solar energy, biomass energy, geothermal energy, ocean energy, tidal energy, etc [49].

2.4. Necessity for China to develop ocean energy

There are abundant ocean energy resources in China, which have great potential to be exploited. Ocean energy development is

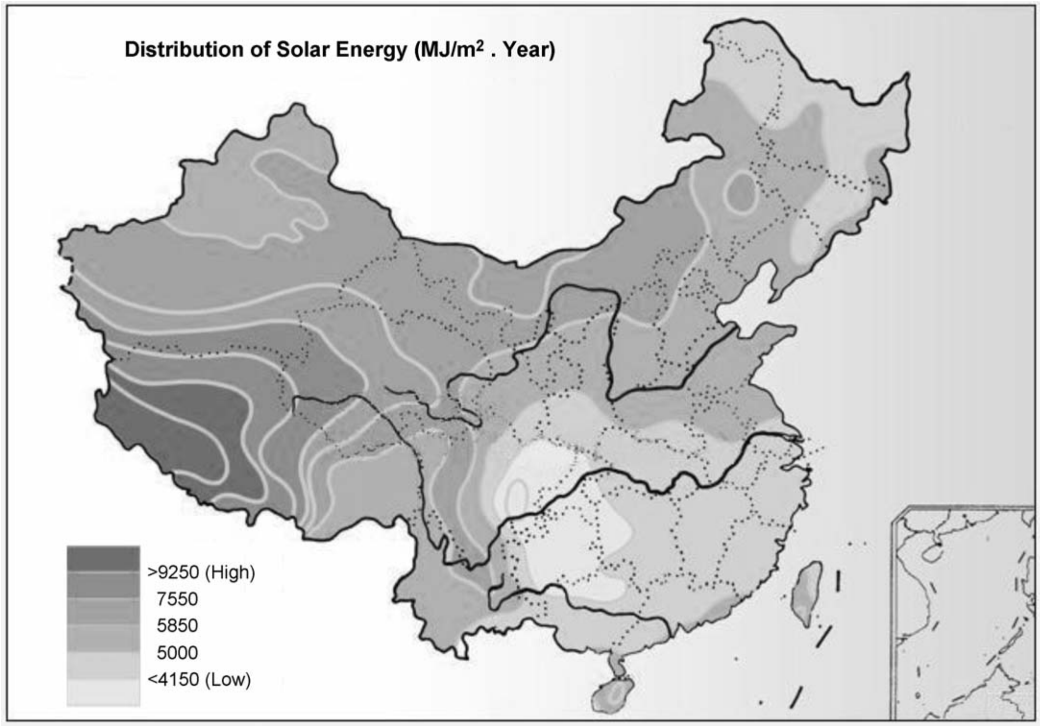


Fig. 3. Distribution of solar energy resources in China (Courtesy of Center for Wind and Solar Energy Resources Assessment of China Meteorological Administration).

strategically significant to the country's sustainable development. At present, the development of ocean energy in China is still in the stage of researching and pilot test and takes a fairly small proportion in the whole energy mix, hence it is essential to promote the development of ocean energy.

There are nearly 870,000 households of 3700 or so villages in the coastal areas of China living without electricity. And there are 433 inhabited islands in China. Most of these islands are lack of electricity, fresh water and fuels supply. So harnessing ocean for power is the most economical and reasonable choice for these areas. To the medium process, it is necessary to further the fundamental research of ocean energy in order to lower the cost of ocean energy's utilization and enhance the reliability of techniques. Moreover, the grid-connected technology also needs to be developed in order to prepare for utilizing ocean energy in large scale [6].

In the long run, exploiting ocean energy resources is an important way to solve the energy problem in China. It is estimated that the total reserve of available ocean energy resources in China can be in the order of magnitude of 1000 GW. By the end of 2008, the total installed power-generating capacity is about 790 GW, which is approximately in the same order of magnitude with the reserves of ocean energy resources. Therefore, if ocean energy was well exploited, China's scarcity of energy supply would be mitigated to a great extent [59,60]. Besides, the energy consumption in China is mainly concentrated in coastal regions where there are densely populated and economically well-developed but short of energy [61]. The coastal provinces create 70% of the nation's GDP with a proportion of energy resources less than 20%. The total energy production of coastal provinces and cities is about 25% of the whole country, but the total consumption has a proportion of 52%. Energy shortage has been the bottleneck which restricts sustained rapid development of coastal regions of China. To solve this problem, China has operated the West–East Power Transmission Project to deliver the coals and hydroelectricity from the west to east parts and developed nuclear power in the east coastal areas, which are uneconomical and still could not meet the energy requirement of southeast coastal regions with a shortage of 2.3×10^8 kW by 2020 [62,63]. China's ocean energy resources distribution is consistent with the regional distribution of the energy demands. So it would be an important way to mitigating energy scarcity of coastal regions by conducting the research on the development of ocean energy in large scale with low cost.

In addition, ocean energy has the advantages of clean, pollution-free and renewable, which are of great practical significant to improve ecosystem, fight climate change, conserve energy and reduce emissions. And ocean energy could also provide energy for exploitation of mineral resources, energy resources and biomass resources [6,21].

Chinese Government has realized the importance of developing ocean energy. It is mentioned in the REL that "The government aids to constructing independent renewable power system in off-grid areas for industrial and domestic energy providing", "The state finance set up special funds for renewable energy development to support constructing independent power supply system in remote areas and islands", "The state grants tax preferences to the projects listed in the guidance for renewable energy industries" [30]. During the period of the 11th Five-Year Plan (2006–2010), China has given great support to the study on ocean energy. And especially the National Hi-tech R&D Program (863 Program) and National Key Technology R&D Program provided financial aids for many ocean energy development projects, which has promoted the research and development of new equipment and the research on the key technology for developing and utilizing the ocean renewable energy. Some demonstration projects preliminarily constructed the technology system of ocean renewable energy development and laid the foundation of commercialization of the technology [6]. The draft of the 12th Five-Year Plan of China is under way and it is expected in the plan that the government would further increase the investment in ocean renewable energy and accelerate the commercialization progress.

According to the development of wind energy and solar energy in recent years, the technology of new energy would develop very rapidly once it was technically matured and a good commercial

operation mode came into being under reasonable policy inclination. Under the background that the government pays much attention to new energy and makes great efforts to support research, development and application of renewable energy technology, China's ocean energy harnessing technology is facing a good opportunity for rapid maturing and progressively commercializing.

3. Ocean renewable energy in China

Generally the ocean energy refers to the energy inherently derived from the ocean, such as tidal energy, wave energy, thermal energy, salinity energy, current energy and chemical energy, exclusive of the fossil fuels of coal, oil, natural gas, natural gas hydrates, etc. which stored in or under ocean floor and the chemical energy source that dissolves in seawater.

3.1. Reserves and distribution of ocean energy resources in China

China has a long coastline and wide sea areas which contains abundant ocean resources. China carried out an investigation on ocean energy resources 20 years ago [64]. And from 2004 to 2009, in a subproject of "Comprehensive Survey and Assessment of China's Inshore Areas and Ocean" project, China's ocean energy resources were surveyed and estimated systematically. It covers the aspects on reserves, density, distribution areas, exploitability and prospects of various forms of ocean energy. Society and environment relevant to ocean renewable energy are also investigated. Key-point investigations were carried out on the islands and coastlines that had good resources conditions, convenient to exploit or capable of promoting the development of local tourism, agriculture and aquaculture and convenient to exploit. There were 107 pre-selective focused areas and 32 key investigated areas [65–67]. A comprehensive knowledge of the ocean energy resources in China was obtained through the investigations.

The energy utilizing ways that technically available or possibly make breakthrough at present are wave energy, tidal energy, marine current energy and ocean thermal energy [68]. 90% of these resources are distributed along the coastal of the conventional energy shorted east China regions such as Shanghai, Zhejiang and Fujian. More than 80% of China's tidal energy resources are distributed in Fujian and Zhejiang and ocean thermal energy is mainly in South China Sea. Sea areas to the south of Yangtze River Estuary are rich in current energy and salinity energy. Concurrently, there are intensive industry and agriculture in the regions of South and East China which are short of conventional energy, and a large number of undeveloped islands are off-grid even lacking in energy and fresh water. China's distribution of ocean energy is matching with the needs of these areas in China and ocean energy is a preferable resource with advantages of in-field usable and no need of long-distance transportation [65–67,59,60].

In terms of reserves and density of the ocean energy distributed in coastal areas, inshore and its adjacent sea areas of China, thermal energy and tidal energy are at optimal level with the highest energy density in the world, tidal energy and wave energy are at the middle level and low level respectively. Comparing reserves of different forms of ocean energy, wave energy and thermal energy are the richest, current energy and tidal energy are less [6].

3.2. Status of ocean energy development in China

Coastal countries pay attention to development of ocean energy. In light of current trends, ocean energy will be one of the important energy sectors in these countries, especially the developed coastal countries. The conditions of various countries show that tidal electric power generation technology is relatively mature while the technologies of wave energy, salinity energy and ocean thermal energy are immature yet and are mostly still in the research and development stages. China's ocean energy utilizing technical level is roughly in step with the world [69].

Preliminary statistics show that the number of R&D units which are or will be working at the development of ocean energy has reached nearly 50, and the number of experts with associate professor or higher ranks have exceed 160 which shows that research team devoted to ocean energy has began to takes shape. Besides, several conventional energy corporations such as China National Offshore Oil Corporation (CNOOC), China Huaneng Group, Datang Group and China Longyuan Power Group have paid attention to the ocean energy and some private enterprises also invest in it, which shows that the development of ocean energy in China presents a brilliant and broad prospect.

The government of China is committed to developing ocean renewable energy. In July 2010, Ministry of Finance appropriated special funds of 200,000,000 CNY to foster the development of ocean energy development for the first time. The funds issued by the State Oceanic Administration (SOA) to several large scale projects lead by some large state-owned enterprise such as CNOOC, Huaneng, Datang, Longyuan, etc. and dozens of research projects in ocean renewable energy development. Participation of enterprises is considered the most significant step to the road of commercialization of ocean renewable energy. This event is considered to be a milestone for China's ocean energy development and the funds will be appropriated every year thereafter.

3.2.1. Tidal energy in China

Tidal energy is the potential energy of water caused by flood and ebb tide. Its principle of operation is similar to hydroelectric generation. Tidal energy can be extracted by building a dam (barrage) across an estuary or coastal inlet, the dam containing turbines to generate electricity. The energy of tidal is approximately proportional to the square of the tidal range and area of the water trapped in the barrage. The long coastline of China contains abundant tidal energy. It is estimated that the theoretical generating capacity of tidal power in China reaches 1.1×10^8 kW and there are 242 potential tidal energy dam sites with installed capacity from 200 to 1000 kW with total capacity of 12.3×10^4 kW and annual energy output of 3.05×10^8 kWh [66].

3.2.1.1. Distribution of tidal energy resources in China. China's tidal energy resources are unevenly distributed. The tidal range of the tides along China's coast is moderate in the world, and the maximum tidal range are half of that in areas with the supreme tidal range of the world, as well as the average tidal range. E.g. the maximum tidal range of China, which occurred in Ganpu of Hangzhou Bay is 8.93 m, while the world's largest tidal range can reach 19 m in Bay of Fundy. As for China, East China Sea has the largest tidal range, South China Sea has the least, and Yellow Sea and Bohai Sea fall in between [66]. Generally speaking, average tidal range above 3 m is of applying value [70]. In China, Estuary mouth of Qiantang River has the most abundant tidal energy, followed by mouth of Yangtze River and then comes the estuaries of Zhujiang, Jinjiang, Minjiang, Ou Jiang, etc. Distribution of tidal energy resources in China is shown in Fig. 4.

China's tidal energy is mainly distributed along the coast of East China Sea. Provinces of Fujian and Zhejiang have the greatest number of potential sites, which are 88 and 73 respectively. Total installed capacity of these sites can reach 1.925×10^4 kW, with annual energy output of 5.51×10^{10} kWh, which occupies 88.3% of the available tidal energy of China. If fully exploited, 20 million tonnes of coal equivalent's energy would be provided for these areas. Besides Fujian and Zhejiang, the north branch of the mouth



Fig. 4. Distribution of tidal energy resource of China's coast. *Sources*: Adapted from Ref. [9] (Mean tidal range: Class I: $A \geq 4$ m; Class II: $2\text{ m} \leq A < 4$ m; Class III: $1\text{ m} \leq H_{1/10} < 2$ m; Class IV: $A < 1$ m).

of Yangtze River (belonging to Shanghai and Jiangsu province), Liaoning and Guangdong have installed capacity of 70.4×10^4 kW, 59.4×10^4 kW and 57.3×10^4 kW respectively. Other provinces and regions have relatively few tidal energy and the minimum in the coastal areas of Jiangsu Province (excluding mouth of Yangtze River) with a installed capacity of only 0.11×10^4 kW. See Fig. 5 [65].

There are many station sites with superior natural conditions and high density energy along China's coastline, especially the southeast coastal areas. Mean tidal ranges of these sites are 4–5 m and maximum tidal range reaches 7–8 m. Among these, some medium-sized station sites such as Dagongban (1.4×10^4 kW, 4.5×10^7 kWh) and Bachimen (3.3×10^4 kW, 1.8×10^8 kWh) in Fujian, Jiantiao Harbor (1.5×10^4 kW, 4.5×10^7 kWh) and Huangdun Harbor (5.9×10^4 kW, 1.8×10^8 kWh) in Zhejiang which have been fully investigated, layouted and feasibility-studied, are worth developing and exploitable in the near future. There are also some planned large-sized station sites that have been investigated earlier while needing to conduct further systematic arguments yet, including the north branch of the mouth of Yangtze River (70.4×10^4 kW, 2.28×10^9 kWh), Hangzhou Bay (3.16×10^6 kW, 8.7×10^9 kWh), Yueqing Bay (5.5×10^5 kW, 2.34×10^9 kWh), etc. [65].

3.2.1.2. Development status of tidal energy in China. The utilization of tidal energy in China starts earlier than other kinds of energy and it is mostly matured in technology. China has constructed the largest number of tidal power plants in the world. From 1958 to 1970s, more than 40 tidal power plants have been built in Shunde and East bay of Guangdong, Rushan of Shandong province, Chongming of Shanghai and other places. Unfortunately, most of the tidal power plants built in this period were out of service due to wrong site selecting, backward technology, conflict service between irrigation and navigation purpose, and inconvenience in use [21]. According to a statics of 1980s, only eight stations are still in service and the number reduced to three at now (See Table 1).

Jiangxia pilot tidal power plant (Fig. 6) is the remarkable one of the three plants. It is located in Jiangxia Harbor, at the north end of Yueqing Bay. Jianxia power plant is the third largest tidal power station in the world, after La Rance tidal power plant in France and Annapolis tidal generating station in Canada [71]. It has started the construction from 1974. The first generator sets of 500 kW started its generation in 1980. The project was completed in 1985, which installed one set generator of 500 kW, one set of 600 kW and three sets of 700 kW with the total capacity of 3.2 MW. In June 2007, the 6th set generator was successfully developed and combined into the grid, and the total installed capacity reached 3.9 MW [72]. For years the engineering staff of Jiangxia plant devoted to industrialization research works of tidal generating and had made remarkable achievements in reliability of the generator sets, sediments reducing in reservoir, erosion protecting, floating method, operating automation and optimal scheduling [73,74]. Since June 2009, automation and safety of the plant have been great improved after technological upgrading for the 3rd and 4th generator sets. According to the latest figures, total power output of Jiangxia pilot

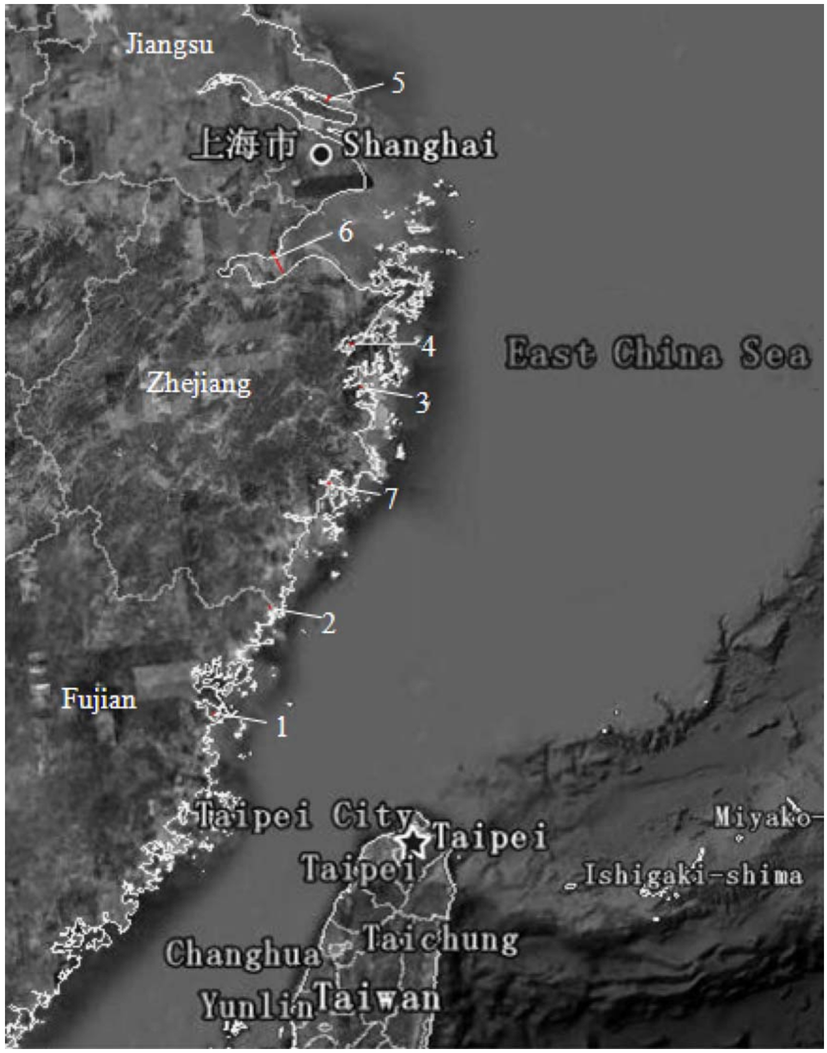


Fig. 5. Some potential tidal power station sites: 1. Daguanban; 2. Bachimen; 3. Jiantiaogang; 4. Huangdungang; 5. The north branch of the mouth of Yangtze River; 6. Hangzhouwan; 7. Yueqingwan.

tidal power plant is 1.62×10^8 kWh since it combined to grid of East China on Jan 26, 1986 [75].

Since Jiangxia power station was constructed and started operating in 1985, development of tidal energy had little progress. No more tidal plant had been constructed, and the existing tidal plants are out of services due to disrepair of generator sets or withdrawn from the market because that their electricity prices were much higher than the large power grid which extended to remote and border areas along coasts [65]. Even Jiangxia power station, which is operating in relatively good conditions, is loss-making. But Jiangxia power station is doing well in comprehensive utilization of reservoir. It makes great profit in planting in reservoir reclamation land, aquaculture and shellfish farming and accumulates abundant experience for optimization of eco-environment [76].

Table 1
Tidal power stations in China.

Name of plant	JiangXia	HaiShan	BaiSha Estuary
Location	WenLing, Zhejiang	YuHuan, Zhejiang	RuShan, Shandong
Installed capacity	3900	250	640
Mean tidal range	5.08	4.91	2.36
Area of reservoir (m^2)	137×10^6	N/A	3.2×10^6
Commissioning date	1980.5	1975.12	1978.8

3.2.1.3. Assessment and advices. So far China's technology of tidal energy development has matured and accumulated a large amount of practical experience. It could enter the stage of extensive development if the eco-environment problem was solved [66].

At present, the price of tidal electricity is much higher than conventional power and lacks competitiveness due to low energy density, high construction costs and less energy generation. Due to



Fig. 6. Jiangxia pilot tidal plant (Photo by Zhou Xuejun).

these reasons there is no large scaled tidal energy plant being constructed in recent years. However, benefits of developing tidal energy outweight the risks to the environments on the whole. If it is developed in the ways of seeking advantages and avoiding disadvantages, tidal energy makes for sustainable development and it meets Chinese government's requirement of constructing resources saving, eco-friendly and harmonious society [77]. Therefore, it is necessary to build scaled tidal power stations in appropriate sites.

In the key domain of NDRC's *Medium and Long-Term Development Plan for Renewable Energy in China* set a target that 100,000 kW tidal power stations would be built by 2020 [37,41,78]. To achieve this goal, a series of preliminary works is being done for constructing tidal power stations in China. The feasibility study of a 10 MW intermediate experimental tidal power station in Jiantiao Port of Zhejiang Province and Daguanban Port of Fujian Province has been worked out. And the planning of the Maluanwan Tidal Power Plant is under way [21].

The government is very cautious in deciding tidal energy plants construction for historical lessons. Before constructing, sufficient evaluation and thorough advanced planning must be done on site choosing of the barrage, impacts on eco-environments and economic profits.

In addition to cautious decision making, it is important to maximizing profits by ways of cutting down costs of equipments, constructing and operating, improving management, optimizing running, raising output and comprehensively utilizing the reservoir when building tidal energy plants.

Furthermore, government's support is necessary for developing tidal energy. The operating status of the existing tidal power plants shows that relatively higher electricity price makes commercialization of the tidal development technology very difficult without preferential policies and subsidies from the government. Government investment should be combined with non-government capital. In regions along coasts with power supply tension or needing deployment of power grid, it should mainly depend on civilian capitals to build tidal power plants and the government should give assistant as much as possible in policies of funds and taxation [79]. For the grid-connected tidal power stations, the government should give them the preferential terms equal to wind energy and solar energy, implementing feed-in-tariffs to improve their competitiveness and encourage development.

For the only remaining tidal power plants, active supporting measure should be taken to gather operating experiences for the planned 10 MW level tidal power plant, and provide testing sites for the development of new materials and devices.

3.2.2. Marine current energy

Marine current energy is the kinetic energy of flowing seawater, mainly the relatively steady ocean flow in strait or water channel and the regular current flow caused by tides. Energy can be extracted from marine current by ways which is theoretically similar to wind power generation. The power of a current is proportional to velocity cubed and flux. Therefore, the higher the speed is, the more valuable an ocean current is. Generally speaking, currents in water channels with maximum flow speed more than 2 m/s have the practical application value. Compared with wave energy, variations of ocean current are more steady and regularly. The most exploitable marine current is the tidal current caused by flood and ebb of the seawater, which has high velocity and varies its speed and direction periodically twice a day. In this paper, marine current energy refers to tidal current energy unless otherwise indicated.

3.2.2.1. Distribution of marine current energy resources in China. - From north to south, distribution of marine current energy resources in China is uneven in sea areas of China which are Bohai Sea, Yellow Sea, East China Sea and South China Sea. Velocity of marine current in most areas along Bohai Sea are less than 0.77 m/s except water channels in Bohai Strait, among which the highest speed reaches 2.5 m/s in Laotieshan water channel in the north end. Current velocity in the Yellow Sea coast is larger than that in Bohai Sea, which is 0.5–1.0 m/s. The areas of Changshan Archipelago, estuary mouth of the Yalu River, vicinity of Chengshantou which located in the top of the Shandong Peninsula and surroundings of Qionggang and Xiangyanggang in Jiangsu have higher speed currents. Coasts of East China Sea, in particular the sea areas of Zhoushan have the most intensive marine current energy resources. The estuary mouth of Yangtze River, the mouth of Hangzhou Bay, the water channels in Zhoushan Achipelago and mouths of some rivers (such as Jiaojiang River, Minjiang River) and harbors (such as Shacheng Harbor, Sandu'ao, etc.) in Zhejiang and Fujian has strong tidal current. Maximum current velocities of spring tides in most of these areas are more than 1.50 m/s and can reach 3.0–3.5 m/s in several special water channels. Marine current is the weakest in South China Sea coast, most areas of which have flow speed less than 0.50 m/s. And a few water channels which located in the mouth of the Pearl River, northwest of Guangdong and coast along Beibu Bay have stronger flows with speed of 1.0–1.5 m/s. Only marine current in the east entrance of the Qiongzhou Strait is the strongest with a flow speed of 2.0–2.5 m/s.

According to the statistics of Chinese Academy of Science (CAS), there are about 13,948.5 MW of tidal current energy technically available in 130 water channels in China. These 130 channels can be divided into three classes in terms of the velocity of tidal flow. And there are 11 class I channels, 41 class II channels and 78 class III channels. As shown in Fig. 7, 95 of the 130 channels are located in the coasts of the East China Sea, which have average power of 10,958.15 MW theoretically, take 78.6% of the total. Zhejiang province, which has theoretically available reserve of 7,090.28 MW, contributes nearly 50% of the total tidal current energy reserve, is ranked first in China. Taiwan, Fujian, Shandong and Liaoning have theoretically available reserve of 2283 MW, 1280 MW, 1195 MW and 1140 MW, respectively, are ranked 2nd–5th, as shown in Fig. 8.

There are some excellent channels with high energy density along coasts of China as shown in Fig. 9. Water channels in sea areas of Hangzhou Bay and Zhoushan Achipelago have the most abundant marine current resources, with the maximum flow speed over 4.0 m/s. The channels in Zhoushan Achipelago, such as Jintang Channel (25.9 kW/m^2), Guishan Channel (23.9 kW/m^2) and Xihoumen Channel (19.1 kW/m^2) are the most promising ones to be exploited. Laotieshan channels (17.4 kW/m^2) in Bohai Strait and Sandujiao channel (15.1 kW/m^2) in Sandu'ao Bay of Fujian are also good sites. And there are other available channels, such as the north channel of Beihuanchang (13.69 kW/m^2) in Shandong, the

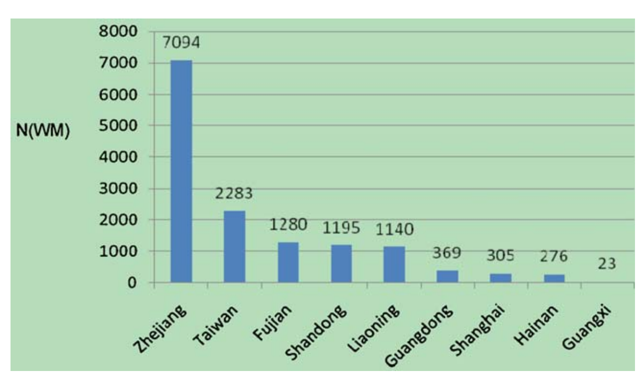


Fig. 7. Theoretical power of marine current in top nine provinces in China [66].

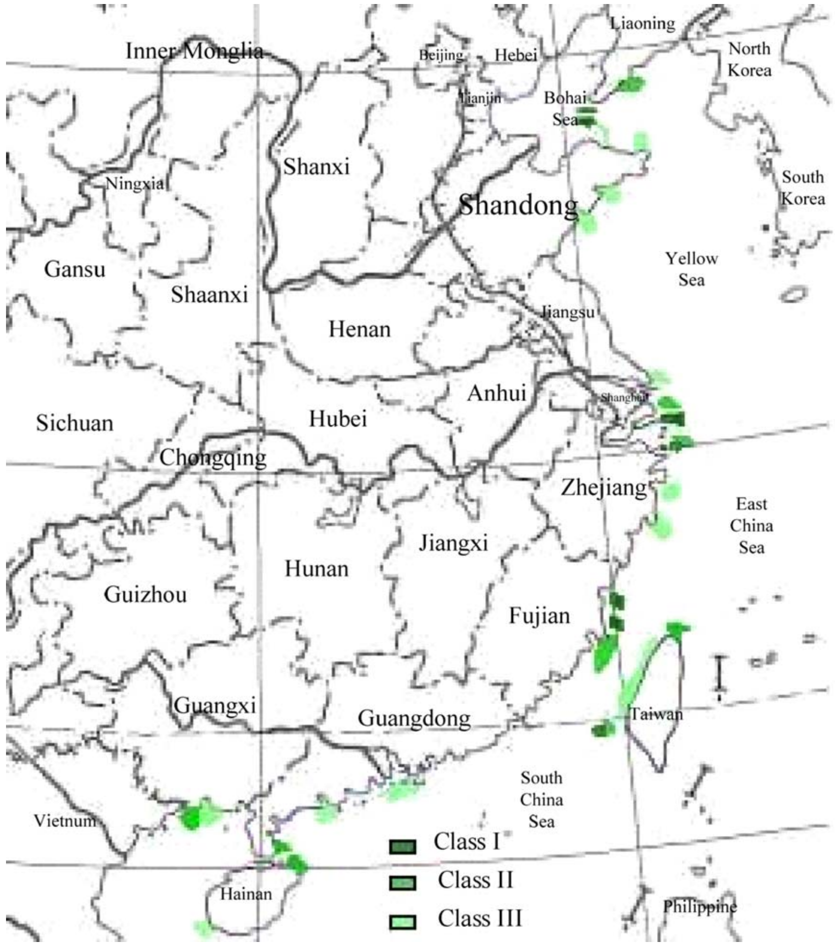


Fig. 8. Distribution of tidal current energy resource of China's coast. *Sources*: Adapted from Ref. [9] (Maximum spring tidal velocity: Class I: $V_m \geq 3.06$; Class II: $2.04 \leq V_m < 3.04$; Class III: $V_m < 2.04$).

north channel estuary mouth of Yangtze River (10.30 kW/m^2), Hangzhou Bay North (28.97 kW/m^2) and channel in southwest of Yuwong Island, Taiwan (13.69 kW/m^2), etc [64,66].

3.2.2.2. Development status of marine current energy in China. - Marine current energy technology in China can be traced back to 1978. At the year, He Shijun, from Dinghai, Zhejiang, made a testing tidal current conversion device and harnessed 5.7 kW electricity at the velocity of 3 m/s in Xihoumen Channel.

Systematic study of marine current started in 1982. Harbin Engineering University (HEU) developed a new straight-blade marine current driven turbine with high efficiency, made laboratory testing of a 60 W prototype in 1984 and then developed kilo-watt level devices. After that, HEU has been working at techniques of marine current energy harnessing. In January 2002, HEU built the first floating moored tidal current turbine in China, a 70 kW prototype system (WanXiang I) in Guishan channel (Daishan, Zhejiang), as shown in Fig. 10. The device consists of two vertical axis rotors, driven systems, control mechanism and floating platform. Each 2.2 m diameter rotor consists of four vertical blades with variable pitch. Thin spokes in tension connect the blades to the hub for the purpose of transferring torque. A shaft connects the hub to the gearbox coupled to the generator forming the driven systems. The rotors, driven systems and control mechanisms are supported by a floating platform, which is kept floating by a pair of hulls. The floating platform then moored to the seabed through a mooring system, which includes four gravity anchors and light chains [80,81]. In 2005, a seabed mounted marine current power plant (Wangxiang II) with 40 kW rated power, was installed by HEU in the channel between Duigangshan Island and Gaoting, Daishan (as shown in Fig. 11). The device consists of two 20 kW straight-blade vertical rotors, driven system and a platform. The platform consists of turbine nacelle, caissons and fixed legs. As a totally submerged system, the driven system and the generator are tightly sealed in the turbine nacelle. From 2007 to 2009, with the support of the National High-tech R&D Program of China (863 Program) and the United Nations Industrial Development Organization (UNIDO), HEU and Ponte Di Archimedes Co. of Italy jointly developed a 250 kW floating vertical axis marine current device, in which a cymbiform platform and the Kobold vertical axis turbine are adopted. In 2009, a project of National Key Technology R&D Program (NKTRDP), Research and Demonstration of 150 kW Tidal Current Power Station Technology was launched. HEU is the leader of the project with collaboration of Shandong Electric Power Engineering Consulting Institute, National Ocean Technology Center, PE-NERC and Gaoting Shipyard. The project is aimed at testing the prototype turbine and demonstrating technology, which will be finished in 2011.

Beside HEU, there are other research institutes, such as the Northeast Normal University (NENU), Zhejiang University (ZJU) and Ocean University of China (OUC) working at development of marine current energy.

From 2006 to 2008, NENU developed a 1 kW floating horizontal axis turbine supported by 863 Program, as shown in Fig. 12. To avoid disadvantages of existing horizontal axis turbine, such as needing pitch adjusting and efficiency dropping in reverse flow, a

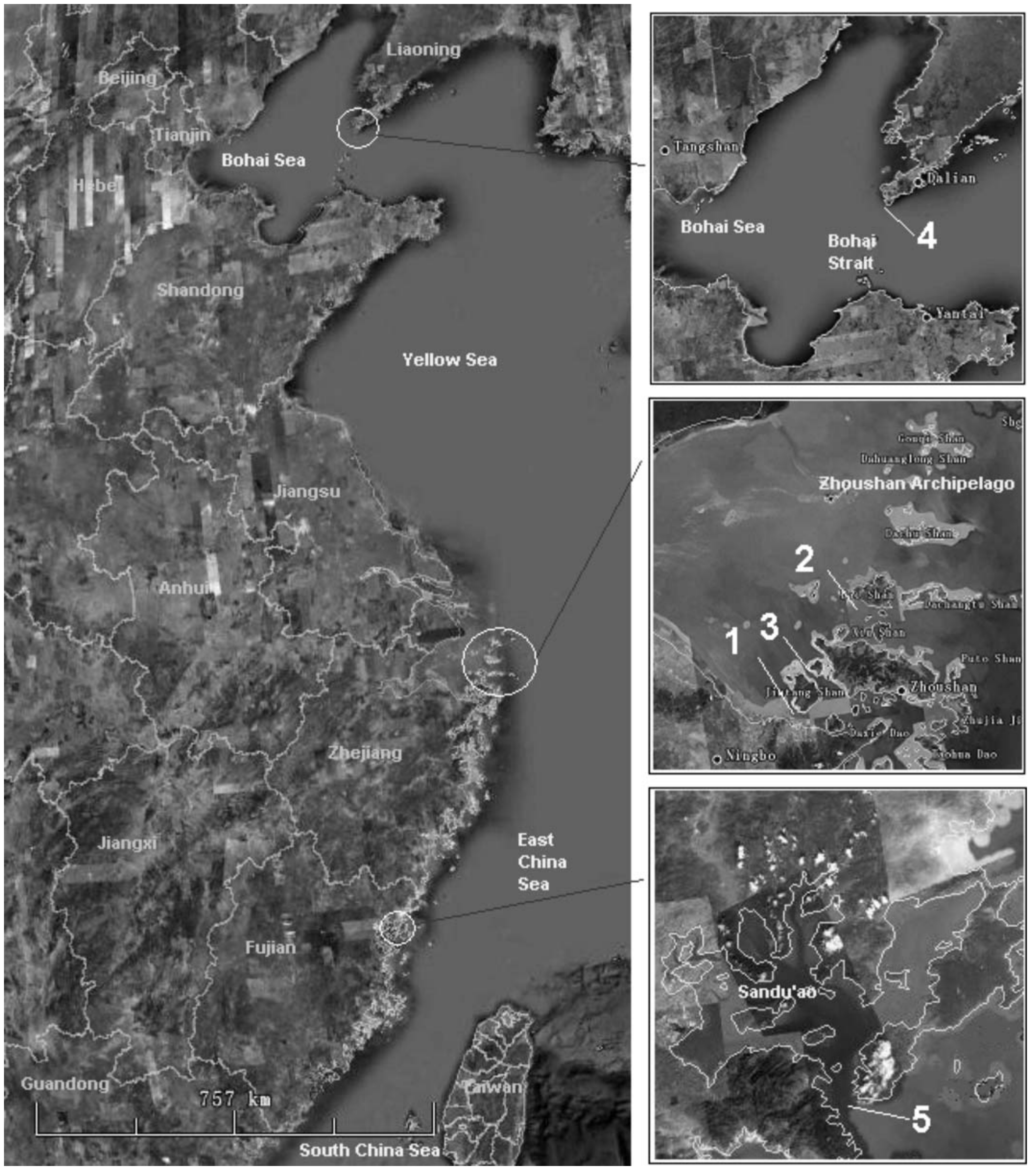


Fig. 9. Locations with high tidal current speed in China. *Source:* Google Earth (4.2.0198.245) 1. Jintang Channel; 2. Guishan Channel; 3. Xihoumen Channel; 4. Laotieshan Channel; 5. Northwest of Sandujiao.



Fig. 10. "Wanxiang I" tidal current pilot plant in Guishan channel (70 kW, 2002, HEU).



Fig. 11. "Wanxiang II" tidal current pilot plant at Zhoushan (40 kW, 2005, HEU).



Fig. 12. 1 kW device with low-speed current (2006, NENU).

flex shaft was adopted in the turbine, attached the horizontal axis turbine with a vertically arranged generator and made the turbine always facing towards the flow, which is the main innovation [82].

In 2008, an improved 2 kW device was tested in the coastal area of Qingdao, as shown in Fig. 13. Now, a 20 kW horizontal axis turbine is being developed by NENU, which is also an 863 Program supported project. The device was planned to be put into water in 2011.

ZJU started study of marine current energy harnessing device in support of NSFC since 2005. In April 2006, a sea trial of 5 kW horizontal axis tidal current turbine was carried out in Daishan, Zhejiang, shown in Fig. 14 [83–85]. In May 2009, by further development, a sea trail of 25 kW device, which has three 2.2-meter length blades, was carried out in Daishan, Zhoushan (shown in Fig. 15). Results showed that the turbine worked well, generating a maximum power of 29.08 kW in a current of 2.4 m/s. It had good self-starting characteristics and can start rotating at 1.37 m/s. And it can also work well at low velocity, producing 1 kW of power from a water flow as low as 0.6 m/s [86].

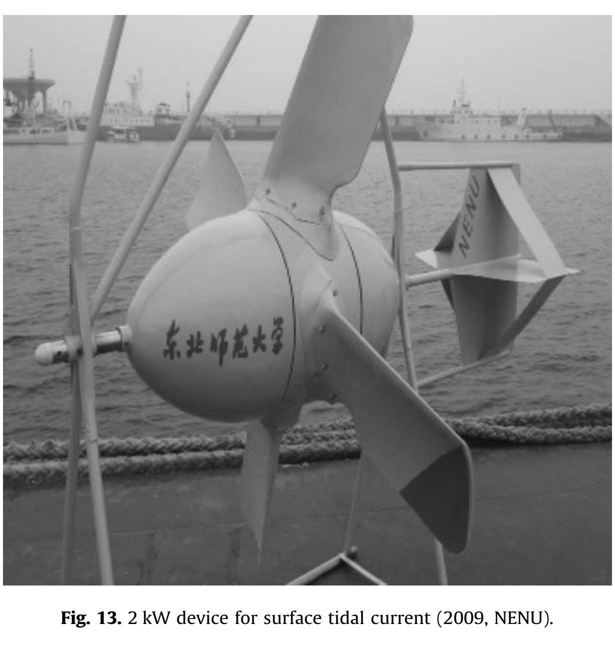


Fig. 13. 2 kW device for surface tidal current (2009, NENU).

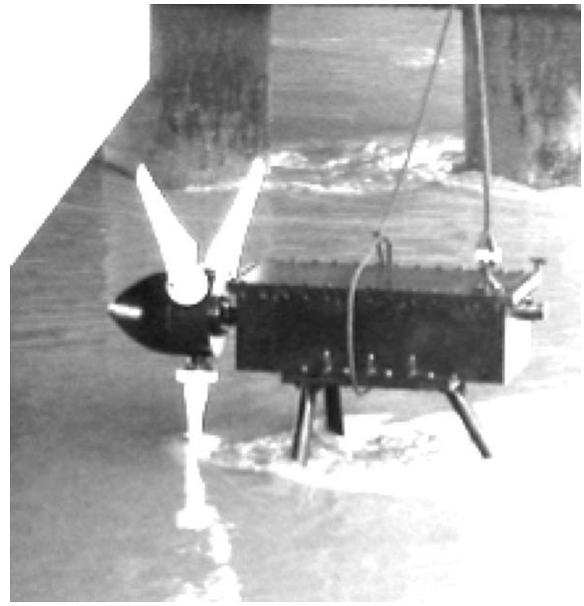


Fig. 14. 5 kW horizontal axis tidal current turbine (2006, ZJU).

OUC started study of marine current energy with a grant from the 863 Program in 2006. It developed a new type of tidal current conversion device, in which flexible material was used as turbine's blades. Rotation direction of the turbine's rotor had nothing to do with the flow direction and the turbine had relatively high efficiency, which made it quite fit for being used in tidal currents [87,88]. The first demonstration system, a floating, moored platform, that holds a flexible vane turbine (as shown in Fig. 16) with a rated power of 5 kW, was deployed in Zhaitang Island Channel in November 2008 (as shown in Fig. 17). Results showed that the turbine performed well [89].

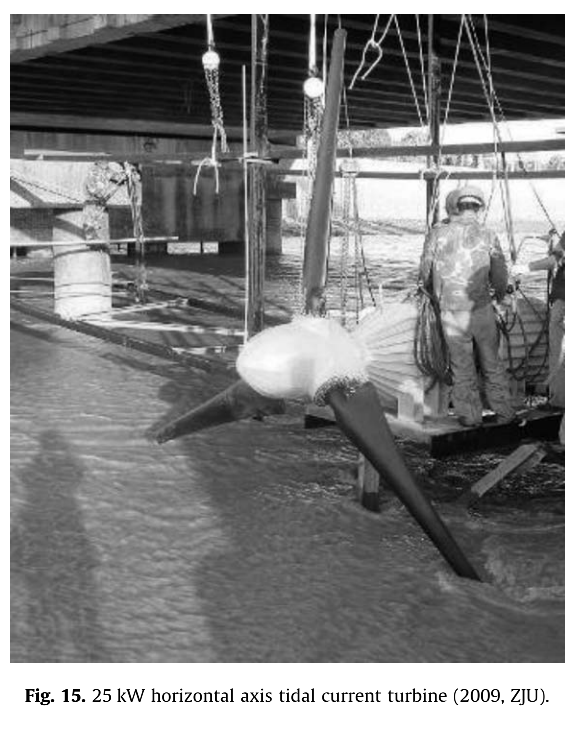


Fig. 15. 25 kW horizontal axis tidal current turbine (2009, ZJU).



Fig. 16. Flexible vane turbine (2008, OUC).

3.2.2.3. Assessment and advices. China's marine current energy development technology is going to maturity now. Some marine current energy devices are in the stages of preparing works before demonstration at present. With solution of the key problems of installation, maintenance, electricity transmission, anti-corrosion and safety, technological breakthrough is expected to make in near future. The next stage, focus of marine current energy research should be concentrated on building of 100 kW level demonstration plants and gathering experiences for construction of marine current energy and comprehensive developing demonstration bases integrated with other types of ocean energy in the long run.

It's hard to evaluate the costs of the electricity generated from marine current energy for there is no commercially operating device at present. But in general the costs are not likely higher than that of the wave energy due to relative simplicity in techniques. In neighboring regions of Zhoushan Archipelago, where there are the best marine current energy resources of the world, once technology matured and large scale developed, the costs could reduced to 0.8 CNY/kWh in estimate, which makes it possible to find markets in isolated islands [6].



Fig. 17. 5 kW tidal current conversion device with flexible vane turbine in sea testing (2008, OUC).

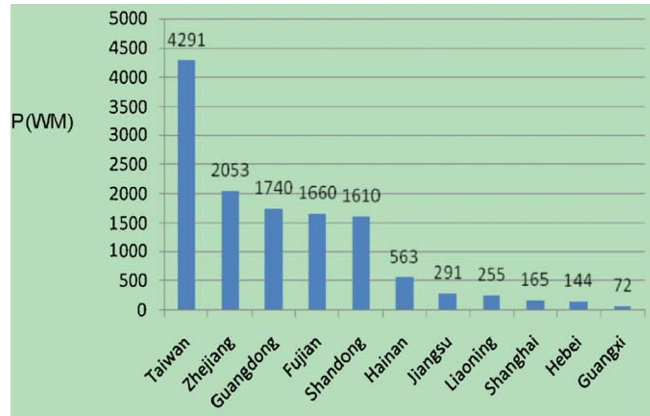


Fig. 18. Theoretical power of wave energy in top 11 provinces in China [66].

3.2.3. Wave energy

Wave energy refers to the kinetic energy and potential energy in waves on ocean surface. A wave's energy is proportional to square of its height and its period of motion, and it is the most unstable energy resources. Wave energy is mainly used to generate electricity. Besides, it can be used in water drawing, heat supply, seawater desalination and hydrogen production etc.

3.2.3.1. Distribution of wave energy resources in China. The theoretical mean power of wave energy resources along China's coasts reaches 12852.2 MW. As shown in Fig. 18, Taiwan has the most abundant resources, which is 4290 MW. Zhejiang, Guangdong, Fujian and Shandong also have massive wave energy resources, which are 1600–2050 MW [64,66]. Although there has the most abundant wave energy resources, due to the fact that technological R&D and special financial support policies are currently not in place, ocean energy still remains relatively unexplored in Taiwan at present [90].

As shown in Fig. 19, Central region of Zhejiang, Taiwan, North to Haitan Island in Fujian and Bohai Strait have the resources with the highest wave energy density (in kW per meter wave front), which can reach 5.11–7.73 kW/m. Followed by the resources in Xisha Archipelago, east Guangdong and north and south Zhejiang, which can reach 3.63–4.05 kW/m. Next to these are the resources in south Fujian and southern shore of Shandong Peninsula, which are 2.25–2.82 kW/m. Wave energy density in other sea areas is relatively low and the resources are limited in reserve. According to the wave energy density and natural environment, coasts along Zhejiang and Fujian should be selected as the prior developing areas, secondly the east Guangdong, Yangtze River Estuary and the middle part of the south shore of Shandong Peninsula [66]. The average wave energy density of China's coasts is 2–7 kW/m, which is much less than that of the countries with the highest wave energy density (40–60 kW/m) such as UK and Portugal. From the global perspective, wave energy density is obviously low in China, which makes development of wave energy difficult [91].

Xiashan Island, Nanlu Island, Dashai Mountain, Yun'ao, Biaojiao and Zhelang, etc. are the sites with good wave energy exploiting conditions in China. Because of high energy density, less variation with season, small mean range of tide, deep nearshore water, petrous seaboard and steep slope, these sites should be the priority areas for wave energy development [66].

3.2.3.2. Development status of wave energy in China. Wave power is the fast-growing marine energy utilizing method after tidal power. The number of patents about wave energy conversion devices has exceeded 1500 [92]. Most of the devices are based on the same basic principles which are oscillating or swing motion caused by

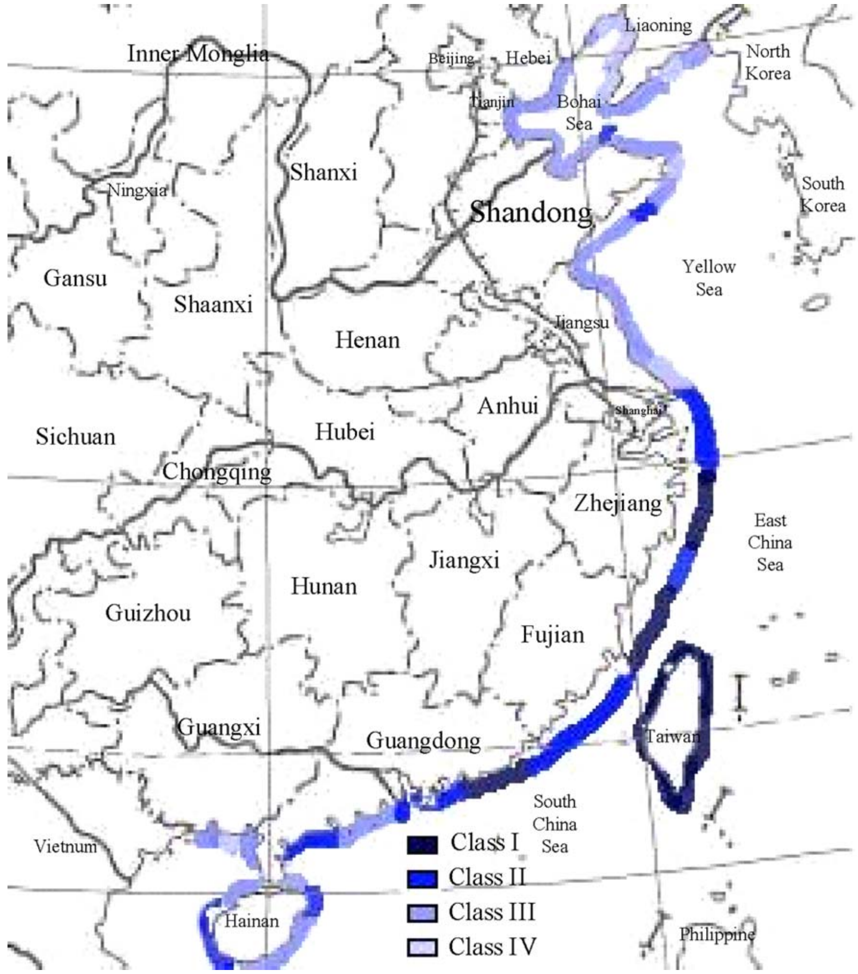


Fig. 19. Distribution of wave energy resource of China's coast. *Sources*: Adapted from Ref. [9] (Annual Mean Wave Height: Class I: $H_{1/10} \geq 1.3$ m; Class II: 0.7 m $\leq H_{1/10} < 1.3$ m; Class III: 0.4 m $\leq H_{1/10} < 0.7$ m; Class IV: $H_{1/10} < 0.4$ m).

waves, pressure variation of waves and water's potential energy caused by climbing effect when wave meets shore side.

Technical research of wave energy development started in 1970s. A 1 kW wave energy buoy was successfully developed in 1975 and a test was made in Shengshan Island, Zhejiang (as shown in Fig. 20) [93]. After 1980s, rapid progress in wave energy development was made in China. Guangzhou Institute of Energy Conversion (GIEC) is the leader institute in this field. In 1984, GIEC developed a 6 W wave energy device which used in marine light. After many years of development, various types of products from 60 W to 450 W were produced and improved for many times. So far there are more than 600 used in China's coasts, and the products have been exported to Japan and other countries. This technology is on the international leading level. Fig. 21 showed one of type of the products.

Research on wave energy development in China began in the Seventh Five-Year period. Ministry of Science and Technology (MOST) and Chinese Academy of Science (CAS) have been giving support for researching of wave energy development. From the 8th Five-Year period to the 10th Five-Year period, financial aids of about 10,000,000 CNY were used to developing two oscillating water column (OWC) wave energy conversion devices of 20 kW and 100 kW, two pendulous wave energy devices of 8 kW and 30 kW, one 5 kW floating wave energy ship and one 50 kW independent wave power producing and water distillation equipment [65]. These researches speeded up wave energy development of China, largely improved technologies of wave energy conversion efficiency, stabilizing wave power output and devices constructing, which made the wave energy development close to application level. Up to now, the main types of wave energy converters in China are shoreline Oscillating Water Column (OWC) wave power plants, oscillating buoy wave power plants and pendulous wave power plants [94,12].

The first pilot wave power plant is located in Dawanshan Island, Zhuhai, built in 1989. It's a 3 kW shoreline OWC wave power plant. Based on its original structure, the plant was rebuilt into a 20 kW plant by GIEC and successfully ran into operation in Feb, 1996 (as shown in Fig. 22). After some improvement, the plant gradually supplied complement power to the island. Since 1989, GIEC had been researching and developing on back bent duct generation buoy and a 5 kW device was successfully developed after stages of performance testing of buoy model, design and manufacturing of the prototype and sea trail. A 100 kW wave energy power station was built with financial aids of MOST's NKTRDP in Zhelang Town, Shanwei City of Guangdong Province in Feb, 2001 (as shown in Fig. 23). It is an in-grid shoreline OWC wave power device and the research was started in Dec, 1996 [95]. GIEC developed a hundred kW leveled off-grid oscillating buoy wave power system from 2002 to 2006, with support of a project of National 863 Program and a CAS Innovation Project. The system absorbs wave energy by an oscillating buoy, absorbed wave energy is converted into hydraulic energy by three plunger pumps, a pressure-maintaining storage device then stabilizes the hydraulic energy, and then the stabilized hydraulic energy is converted into stable electricity output by a

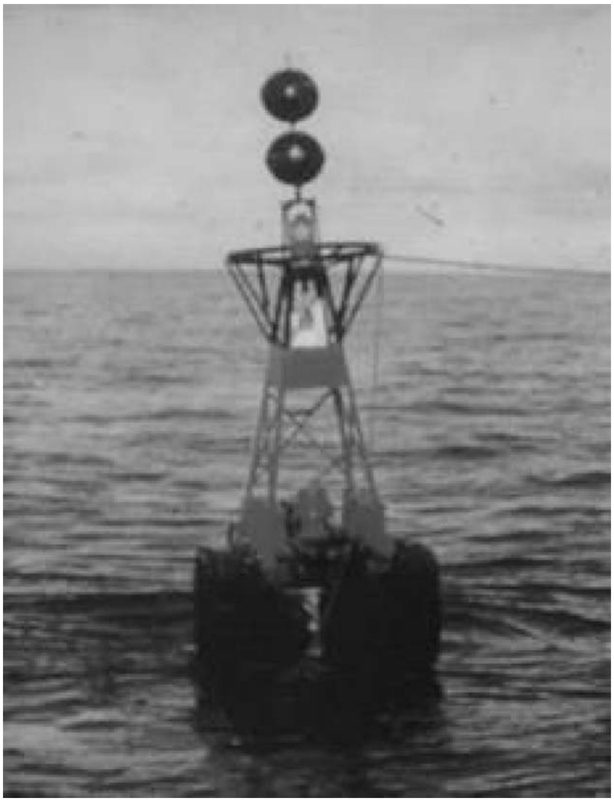


Fig. 20. 1 kW wave energy buoy (1975, GIEC).



Fig. 22. Dawanshan onshore OWC wave power plant (20 kW, 1996, GIEC).

generator driven by hydraulic motor. Testing in actual sea environment shows that conversion efficiency of the system is higher than 50%, the quality of the output power closes to that of the diesel generator so that it can be directly used. The energy consumption of the system itself is only 0.4 kW and the system can work well in small wave conditions. This system was the first wave energy system that can steadily generate electricity independently with the electricity grid or other power system in the world. Conversion efficiency, stability of output and energy consumption of itself had reached the world advanced level [93].



Fig. 21. BD102C wave energy device for beacon light (GIEC).

The Ocean Technology Institute (Now known as National Ocean Technology Center (NOTC), in Tianjin) of SOA set up a 100 kW pendulous wave power plant (as shown in Fig. 24) in Daguan Island of Aoshanwei town, Jimo, Qingdao, Shandong, which came into service since September 1999. The plant puts out more than 800,000 kWh per year and reduces 350 tons of coal consumption compared with coal thermal power plant. So far the plant is still the power supplier of 120 islanders of more than 30 families [92].

GIEC is developing a high efficiency floating wave energy device which has the ability of anti-typhoon. Aimed at reducing costs of wave energy, a new technology will be used in the device to modify the duck. The modification will overcome the drawback of poor resisting ability against wave while keeping the advantage of high



Fig. 23. Shanwei onshore OWC wave power plant (100 kW, grid-connected, 2001, GIEC).



Fig. 24. The pendulum-type wave energy conversion device in Daguan Island (100 kW, 2000, NOTC).

efficiency. Innovation in construction method would largely reduce building difficulties and costs. This research is expected to reach advanced level of the world in efficiency, stability and reliability [92,6]. NOTC and OUC are also researching on pendulous and shoreline OWC wave energy devices presently with aiding of NKTRDP and 863 Program [6].

3.2.3.3. Assessment and advices. Wave energy developed rapidly in China. Technology of mini wave energy devices has matured and small scaled shoreline wave energy technology has been in the world leading position. But in general, wave energy technology in China is immature. The existing wave energy devices in China are still deficient in many aspects, such as high cost, low efficiency, poor reliability, poor stability and small scale [12].

In recent years, some large scaled wave energy devices emerged in Europe, which greatly reduced the prices of the electricity generated by wave energy. The average price has dropped to below 10 euro cents per kWh, which is close to the average power price of EU. From the trend of current development of wave energy technology, it is possible for the costs of wave energy in Europe substantially reduced to below that of the thermal power [6]. At present, wave power has a high price about 2–3 CNY/kWh in China. From the point of present technology, it is impossible for the price to reduce to that of the wind power. The high price limited wide utilization of wave energy. Therefore, presently it should be aimed an development in the fields where conventional power can not reach such as isolated islands, drilling platform and deep ocean mine etc., in which wave energy is possibly the cheapest energy resources. The technology could be widely used after it was matured and the price dropped notably [92]. Besides reducing the price, the stability of the electricity should be improved and independent power supply system should be developed so that wave energy can be directly used by users.

China's wave energy generation system still remained in 10–10^2 kW level so far. Even the long-term goal by 2020 is to develop wave power plants of 10^2–10^3 kW level. In contrast, the wave power plants in advanced countries as Norway and Britain have developed from 10^2 kW, 10^3 kW to 10^4 kW level. So there is a long way to go for practical application of China's small scaled wave power generation [92]. According to current technical level, China's wave energy development can be introduced into demonstration operation stage and cannot be commercialized in the near future. In the next stage, it is better to build 10^2 kW leveled devices and solve the problems of costs, efficiency and reliability. By 2020, a MW leveled wave power plant farm should be constructed and connected to the grid [6].

Although China has been investing in development of wave energy, in general the invested funds are still less when compared with the advanced countries. Shortage of the funds has negative effects on development of wave energy. Hence more support should be given by the government for further maturing and coming into utility step by step of the technology [92].

3.2.4. Ocean thermal energy

Energy can be extracted from the difference in temperature between warm surface water and cold deep ocean water. In most of tropical and subtropical sea areas, the temperature difference is more than 20 °C (36 F) between surface and water in depth of 1000 m as a result of heating effect of solar radiation. It is estimated that the power would be 2×10^{12} W if the temperature difference was used to produce electricity. The ocean thermal energy conversion (OTEC) is a technique for using the temperature difference of ocean water to make a thermodynamic cycle through heat engine to produce power.

3.2.4.1. Ocean thermal energy distribution in China. According to literature of China's water temperature measurement, theoretically available reserve of ocean thermal energy in China's ocean sea areas is estimated about 1.5×10^8 kW, by far the most of it is in the South China Sea, the largest one of China's seas. The South China Sea is a typical tropical ocean which located in south of the Tropic of Cancer. It has vast areas and the areas that depth more 800 m are 1,400,000–1,500,000 km^2. The mean temperature of the surface water is more than 25 °C and the temperature below 500–800 m is below 5 °C. The water temperature differences are 20–24 °C. Vast ocean thermal energy resources are contained in the South China Sea. According to preliminary calculations, theoretically reserve of the South China Sea is $(1.19–1.33) \times 10^{19}$ kJ, technologically available energy (assuming the thermal efficiency is 7%) is about $(8.33–9.31) \times 10^{17}$ kJ and practically potential capacity (Assuming that operate time is 50% and 10% of the reserves are used) can be $13.21–14.76 \times 10^8$ kW [66].

Surface temperature of the water in sea areas to the Taiwan Island is 24–28 °C all the year round and the temperature below

500–800 m depth is below 5 °C with 20–24 °C difference. It is estimated by Taiwan experts that the ocean thermal energy reserve is about 2.16×10^{14} kJ in that area [66].

From energy density, reservation and conditions of exploitation point of view, the middle range of the South China Sea and the sea area to the east of Taiwan Island is the desirable region for development of ocean thermal energy in China.

3.2.4.2. Development status of ocean thermal energy in China. Ocean thermal energy conversion, is abbreviated as OTEC, basic principle of which is to use comparatively warm surface water to heat a working fluid to create vapor and drive a turbine generator and use cold water from deep ocean to condense the vapor back into a fluid. There are mainly three types of OTEC systems: closed-cycle, open-cycle, and hybrid which combine both advantages of the former two [96,97].

To date, OTEC technology has achieved considerable development in forming of the thermodynamic cycle, high efficiency compact heat exchanger, selection of work fluid and marine engineering etc. and many technology have been maturing.

Study of OTEC started fairly late. In 1980, Taiwan Power Company made a study on technology of power generation by using residual heat of nuclear power plant along with OTEC. In 1985, GIEC studied on open-cycle OTEC using a method called droplet elevating cycle. The method increased potential energy of the seawater by using temperature drop between surface and deep water. By estimation, seawater would be elevated to 125 m height by released heat and drive the turbine when temperature decreased from 20 °C to 7 °C. The method reduced the size of the system and increased density of thermal energy. In 1989, GIEC set a record that elevated droplet to 21 m height in laboratory. They also studied on open-cycle process and constructed two experimental devices with capacity of 10 W and 60 W respectively [98]. From 2004 to 2005, Tianjin University made theoretical study on close-cycle and hybrid OTEC systems and developed a 200 W saturated ammonia gas turbine. In the 10th five-year period, the First Institute of Oceanography of State Oceanic Administration carried out a research on development of a unit of 15 W close-cycle OTEC system [6]. There are also other research institutes doing researches on OTEC by the support of provincial and municipal leveled S&T plan. ZJU, for instance, is studying on seawater desalination system based on OTEC with supporting of a major project of Prosper the Ocean with Science and Technology Plan of Zhejiang Province [99].

At the moment, two notable research works are ongoing. One is an 863 Program granted project called "research on seawater desalination technology based on ocean thermal energy", by which a new type of ocean thermal energy based seawater desalination experiment system is build. The other one is a NKTRDP project called "research and experiment of 15 kW thermal energy power devices", signification of which is to construct the first practically applicable ocean thermal energy power device in China [6].

Besides OTEC, seawater-source heat pump technology (SWHP) is another promising way to utilize ocean thermal energy. It is reported that Qingdao Power Plant has built the first SWHP system in China in November, 2004 [100]. Related data show that the cost of winter heating by using SWHP is 15 CNY/m^2, compared with 25 CNY/m^2 of coal heating. During the 2008 Olympic Games, Olympic Sailing Venue of Qingdao used the system as the power sources for air conditioning.

3.2.4.3. Assessment and advices. Generally speaking, development of ocean thermal energy is still at the stage of study. Although considerable progress has been achieved in aspects of form of the thermodynamic cycle, high efficiency compact heat exchanger, selection of work fluid and marine engineering, other aspects such as technology of construction, anti-corrosion and sealing are still immature. Therefore the main challenge for development of ocean thermal energy technology is economy and reliability for long time operating.

Compared with coal firing and nuclear power, ocean thermal energy power plant has high costs in construction, but the operating cost is very low with advantage of no fuel consumption. Therefore, although the cost for each unit of electricity is high in currently existing ocean thermal energy power station, as the improvement of design and construction technology, the total cost of the power plant would be decreased gradually. Ocean thermal energy power plant has long working life and few expenses for running and maintenance. If building cost reduced to certain level, the power price would be cut down to market acceptable range. Additional to power generating, OTEC can be used to produce fresh water, air conditioning and be combined with lifting system of deep ocean mining. These byproducts of OTEC would contribute to lowering the cost of per unit output power. Therefore, independent live spaces can be built based on OTEC and the device can be used as supporting system for offshore power plant, seawater desalination plant or oceanic mining, marine city and marine ranch. In a word, higher profit can be yielded only by synthesis utilizing ocean thermal energy [97,6].

3.2.5. Salinity gradient energy

Salinity gradient energy or osmotic energy is the chemical electrical potential energy between seawater and fresh water or between seawaters with different salt concentrations. It mainly exists in the positions where rivers meet the sea. Salinity gradient energy is the ocean renewable energy resource with the highest energy density. Usually the chemical electrical potential between seawater (35‰ salinity) and fresh water has energy density equivalent of 240 m water head. This head can be achieved by placing semipermeable membrane (allow water molecules pass through and hydrated ions are blocked) in border between the salt water and the fresh water. The head can directly drive the turbine to produce power [66].

3.2.5.1. Salinity gradient energy in China. Reserves of salinity gradient energy mainly depend on the volume of the water flow into the sea. China has a long coast and a lot of rivers run into the sea. Rich salinity gradient energy resources are contained in the estuaries of rivers. By estimation, annual water flux from rivers to sea is about 1.6×1012 m^3, in which the flux of 23 major rivers accounting for 1.4×1012 m^3. It is calculated that the salinity gradient energy resources along China's coasts are 3.58×1015 kJ and the theoretical power is about 1.14×108 kW [66].

Moreover the salinity gradient energy resources in China are unevenly distributed in geography. The resources in Yangtze River Estuary and its south occupy 92.5%. Especially in the estuaries of Yangtze River and Pearl River exist the richest resources of salinity gradient energy. And these two regions are exactly located near Shanghai and Guangzhou which are developed in economy with large energy consumption. The salinity gradient energy resources are relatively scarce in the north of China. And that the rivers to the north of Shandong Peninsula have 1–3 months freezing period in winter, which is disadvantageous for exploiting all year round [66].

3.2.5.2. Development status of salinity gradient energy in China. At present, there are mainly three types of power-generating technology of salinity gradient energy, which are pressure-retarded osmosis, vapor compression and reversed electrodialysis [101]. Since the concept firstly brought up in 1939, there is no practically available salinity power station come out by now. Presently only Israel has built a 150 kW experimental osmotic power device and Norway built a 5 kW osmotic power pilot plant

at Tofte. It seems there is a long time to go before osmotic energy is exploited in large scale.

China's Xi'an Institute of Metallurgic and Architecture (now known as Xi'an University of Architecture and Technology) made experimental research on elevated tank system in 1985. The upper tank is about 10 m above the permeator. 30 kg dry salt was used for working of 8–14 h and generated 0.9–1.2 W electricity. The key technology of osmotic energy development lies on membrane. Unless the permeation flux was improved by one order of magnitude and the seawater could be used without pretreatment that the technology of osmotic energy development would be commercialized [102].

3.2.5.3. Assessment and advices. Although the principle of the salinity gradient energy exploitation is simple, there are lots of difficulties to be solved to achieve large scale and industrialization. Some experts hold that salinity gradient energy exploitation is difficult to be practically applied and commercialized, investment in it would be unadvisable and the environment impact also cannot be neglected under present conditions of technology and process. Therefore, few researchers in China does further research on it after doing some theoretical researches and putting forward some kinds of energy conversion devices [65].

4. Conclusions and perspectives

Under double pressure of rapid economy development and environment protection, to develop renewable energy and raise the proportion of renewable energy in the whole energy mix is the only practical way to maintain future sustainable development for China. The government set feasible long-term planning for renewable energy development and ensured it's carrying out by a series of policies and legislation and institutional reform. Due to pressure of GHGs emission and over fulfill of targets of the 11th five year, the targeted goal set in *Medium and Long-Term Development Plan for Renewable Energy in China* is expected to be modified higher.

After a long period of rapid development, China's renewable energy, especially the wind energy and solar energy has been greatly improved. But the proportion of renewable energy in the whole energy mix is still small and the issue of mismatch between economy and energy in east and west of China exists. Harnessing the rich marine energy in China's coast regions is an important approach to solve this issue. So it is necessary for China to develop ocean energy and made it a supplement for existing renewable energy categories to meet the energy demand of the areas and islands that difficult to use traditional energy.

China's ocean energy resources are quite rich and their distribution fit well with energy demands in coastal regions of China. There are considerable reserves of tidal energy, wave energy, marine current energy, ocean thermal energy and salinity gradient energy, having great developing potential.

After years of development, ocean energy harnessing technology has been getting maturity. Some kinds of the ocean energy technology are expected to engineered and achieve commercialization, and then industrialized. From the technical maturity point of view, tidal power generation technology is the most mature one and it may cause possible environmental impact than the others. So its development should be supported under the premise of careful decision making. In the short term, China's ocean energy development is mainly in tidal power generation and 10 MW leveled tidal power plant should be build at present. Technically solving problems of reducing costs of devices and construction and improvement of reliability should be focused on. Wave energy and marine current energy development technology is close to maturity and could step into demonstration operating stage in the near future. At the next stage, development of wave energy and marine current energy should focus on building hundreds kW level demonstration generation devices and get experiences for scaled commercial operation in the future. In China, OTEC is still at the stage of experimental study, matured in theory and technology, but has a lot of difficulties in engineering. Emphasis should be focused on problems of oceanic engineering, anti-wave and anti-corrosion. Building hundreds kW level OTEC pilot power plants should be set as target of long-term planning.

As other renewable energy, development of ocean energy is a long-lasting and complicated process. In addition to national policies support, technological breakthrough and well-functioning market operation are needed to raise competition of ocean energy and ensure a better development. For this purpose, the government should take measures as following: (1) increase scientific and technological input. Social strength and non-government capital must be put into researches of ocean energy development as well as investment of national science and technology development planning; (2) establish strategic position of ocean renewable energy, incorporate it into national planning and give aids to development of ocean energy by preferential policies and economic means of tax cuts and feed-in tariff etc. (3) Make great effort to industrialization development, seek a way of low cost and large scale development to improve economic returns and market competition.

Ocean renewable energy faces a good development opportunity and China has offered a favorable environment, so there is much reason to believe that ocean energy will get greater development in the future and contribute more to national economy.

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